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The Use of Auditory Output for Time-Critical Information

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

OBJECTIVE

The objective of this research was to develop and evaluate auditory icons as an advanced alerting technique that uses the auditory sense for alerts in the Combat Information Center (CIC). The immediate goal was to compare operator performance using voice alerts and auditory icons with the current buzzer condition. These objectives resulted from a thorough review of the literature which identified the different parameters involved in audio alarms and the pertinent attributes of auditory icons.

DESCRIPTION OF STUDY

Naval subjects performed a visual tracking task on a scenario simulation of the CIC. Alerts were presented by voice, auditory icons, or buzzers. Four different causes for alerts were presented for operators to detect and identify (ASW launches, illuminator faults, harpoon status, and radar jams).

Within the auditory icon condition, four different types of auditory icons were used (one type for each alert). The four different types of icons were: nomic or iconic (sound like the event itself); (2) metaphorical (mappings make use of similarities between the event to be represented and the sound); (3) symbolic (rely on social convention and are arbitrary) and (4) abstract (no relationship with the event but learned for a specific purpose). A family of icons was developed for each alert so that three related sounds corresponded to three alerts of each alert cause.

RESULTS

1. Overall, the results showed that both voice and auditory icons improved detection and discrimination of alerts compared to the buzzer condition currently used in the CIC.

2. There were differences in detection and discrimination accuracy between the types of auditory icons used in this study. The nomic icons helped subjects discriminate and detect alerts significantly better than voice alerts or buzzers. Detection and discrimination accuracy was high with abstract icons.

3. Voice was superior to the symbolic icons and buzzers in reducing errors. The reason may be because the repetition rates of the symbolic icons were identical, thus, they appeared to confuse the subjects.

4. Both voice and auditory icons significantly improved discrimination and detection for those subjects with many errors. Even the metaphorical icons were superior to the buzzer condition for those subjects with many errors. In other words, using voice and auditory icons, the high error rate group improved so much that both the high error rate and low error rate groups were nearly equivalent. An important finding was that using these advanced alerting techniques made poor performers nearly as proficient as good performers.

5. Only voice alerts reduced response time. However, pilots have expressed irritation about voice alerts after long use. For this reason, auditory icons may be better suited to frequent alerts than voice. In actual Navy tasks, small time improvements are often not as important as accuracy in detecting and discriminating alerts.

6. All of the subjects, except one, preferred the auditory icons and voice alerts. The subjects indicated that a combination of the two would provide an improvement to the present buzzer system.

RECOMMENDATIONS

1. Auditory icons are feasible as alerts in the CIC. However, auditory icons need to be easily discriminated and detected. Therefore, all the attributes pertaining to audio alarms and sounds need to be considered before the icons are developed.

2. Auditory icons may be better suited to alerts than voice because voice has been found to be irritating and there is a possibility that voice may be "tuned out."

3. Auditory icons for urgent alerts in the CIC need to be continuous. However, the amplitude of less urgent alerts should be lowered and repetition rates decreased after the initial sounds For information alerts, only soft background sounds should be used.

4. Movie sound effects may be better than everyday sound effects for auditory icons. More research is needed for selecting the best sounds to use for alerts in the CIC.

5. Families of sounds need to be developed for related alerts.

6. Future research should focus on developing auditory sounds for all alerts in the CIC.

7. Auditory icon applications to 3-D sounds for alerts in the CIC need to be researched .

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INTRODUCTION

The overall goal of this research was to develop and evaluate an advanced alerting technique that uses the auditory sense as well as the visual sense for alerts in the Combat Information Center (CIC). This technique can enable tactical officers to make more accurate and quicker decisions regarding alerts. This research will answer the following questions:

(1) Will voice advisory or auditory icons reduce time to attend to alerts and/or increase probability of alert detection?

(2) Will voice advisory or auditory icons improve discriminability of alert types to permit selective attention?

For a tactical officer to make critical decisions, time-critical information needs to be highlighted. Many researchers have shown that auditory alerts combined with visual alerts decrease response time and attract the operator's attention quicker than visual alerts alone (Chillery & Collister, 1988; Hellier & Edworthy, 1989; Kemmerling, et al., 1969; Nugent, 1988; White & Parks, 1985). Only a few scientists in the United States have looked at the use of auditory icons for presenting information on computer systems. (Gaver, 1986, 1988, 1989; Blattner, Sumikawa, & Greenberg, 1989; Sumikawa, 1985). Other scientists have studied how humans code and use acoustic information (Bennett, et al., 1983; Buxton, 1989). An auditory icon may have an advantage over speech because of the gestalt nature of icons versus the serial nature of speech.

Background

One must perceive the attributes of sounds to identify the source of everyday sounds (Gaver, 1988). Attributes such as size, weight, and material are noted by the listener. Action sounds can also be distinguished such as pouring water or running feet. The capability for identifying the cause of a sound depends on how well individuals can form a mental picture of the event. The sound must be clear and similar to a mental stereotype (Ballas, Sliwinski, & Harding; 1986). Most listeners easily recognize a breaking glass. In contrast, musical listening involves sensations of sound. One does not search for an underlying event but only listens to the attributes of music (Gaver, 1988). Ballas and Howard (1987) found subjects described the actual event causing the sound rather than the attributes of the

sound itself. People do not describe a breaking glass in terms of the tinkling sound of glass breaking, but they describe the event itself when asked about the sound. Even computer users learn the meaning of auditory icons.

Interesting research on the recognition of isolated sounds was conducted by Ballas, Sliwinski, and Harding (1986). They studied isolated sounds to determine if the Hick-Hyman law applied to recognition of these sounds. The Hick-Hyman law refers to searching memory for the cause of a sound. As the causes increase for a particular sound, memory search time increases. These authors found this to be true. When many events could cause the same sound, response time significantly increased. The uncertainty values did correlate with mean response times.

Auditory sounds are essential for conveying information. Driving a car is an example of how audio cues convey information. One can drive while conversing with a passenger and still monitor the radio. At the same time, one hears the clicking of the turn signal and the audio cues from the engine for shifting a manual transmission. In addition, one is aware if the car makes a strange noise or if a police siren is in the area (Buxton, 1989).

Audible tones are produced in conjunction with some street lights to indicate to blind people when to cross the street. Where these sounds are absent, blind people use the sounds of cars stopping and starting to judge when to cross the street (Buxton, 1989). In addition, it has been shown that scores for video games decrease when audio cues are absent (Blattner, Sumikawa, & Greenberg; 1989).

Types of Auditory Icons

The current research used four different types of auditory icons: nomic (also called iconic), metaphorical, symbolic, and abstract icons. Nomic or iconic sounds relate directly to events. Examples are the tinkling of breaking glass or slamming of the door. In computer displays, these icons relate to some event in the model world, not to underlying events in a computer system (Gaver, 1986). Gaver (1989) also points out that nomic sound representations are not always possible in computer systems. Thus, listeners may have to use their imagination or generalize their knowledge about everyday events. He suggests that movie sound effects be used when

necessary rather than typical everyday sounds. New sounds may even have to be developed for use on computer systems. Cute sounds such as "Donald Duck" sounds are not good representations because they become irritating when one hears them over a period of time.

Metaphorical icons make use of similarities between events and the sound, such as a falling pitch for a falling object. Nomic icons relate to the model world more directly than metaphorical ones which relate better than symbolic ones (Gaver, 1986). Symbolic icons rely on social convention and are essentially arbitrary. Sirens and applause are examples of symbolic icons (Gaver, 1986). Buxton (1989) points out that people learn symbolic sounds and automatically recognize a clock striking midnight or a train whistle.

Abstract icons are sounds that have no relationship with the event but are learned for a specific purpose. All types of auditory tones are examples of abstract icons. Warning tones or buzzers are examples of this type of sound. The difference between abstract icons and other warning sounds, such as tones or buzzers, is that the abstract icon is structured so one can identify the particular warning by learning the meaning of the abstract icon. When using tones for warning or information, one must be cautious about using a simple tune. A simple tune becomes tiresome when heard 10 or more times a day (Blattner, et al., 1989).

Sound Parameters

Parameters of sounds include frequency, pitch, amplitude, timbre, dynamics, and repetition rates. "Pitch is the psychological attribute that corresponds to the physical attribute of frequency" (Patterson, 1982). Frequency is defined as the number of occurrences of a waveform in a second [cycles per second (cps) or hertz (Hz)]. Gilmore (1985) recommends that audio signals have a frequency between 200 Hz and 5000 Hz. (preferably 500 Hz). With only small changes in signal intensity, 1000 to 4000 Hz is recommended. High frequencies are usually associated with "up" and low frequencies with "down" when pitch is used as an audio cue. Wittlieb-Verpoort and Peret (1987) tested different pitches (pure tones) from 300 Hz to 800 Hz. Subjects were able to monitor five different pitches if they were arranged to facilitate discrimination.

The timbre of a sound refers to the quality of the sound such as warm, harsh, etc. (Blattner, et al., 1989). In music, timbre may refer to the type of musical instrument. The same musical note is different when played on piano than with a clarinet. The timbre does not rely on harmonics alone but on how harmonics are grouped into auditory streams (Bregman, 1984). An auditory stream is a mental representation of the sound.

The dynamics of a sound indicates the direction. A musical three-note icon that changes from soft to loud can indicate direction or movement (Blattner, et al., 1989). Thorning and Ablett (1985) point out that similar repetition rates can cause confusion. If two sets of alternating tones are separated widely in pitch and the repetition rate is the same, a listener has trouble discriminating between the two sets of alternating tones (Gaver, 1988). However, if the repetition rate differs, then listeners can hear the difference between the two sets of alternating tones. In summary, confusion is more likely with similar repetition rates.

Amplitude of a sound can be important. Mulligan, et al. (1984) reports that response time is faster with loud sounds than with soft sounds. Thus, in designing a warning system, a loud acoustic stimulus would be appropriate for urgent alerts. In addition, when binaural messages are presented, the parameters of pitch and loudness exert a prominent influence. Mulligan, et al. (1984) recommends that an alerting message be 10 decibels (dB) greater than a competing message if both messages are presented to the same ear.

<u>Audio Alarms</u>

Research has shown that signal detection rates are higher on computer displays when auditory feedback is added to visual feedback. Almost all of the recorded research has focused on the use of sounds for attracting attention to alarms. The sounds do not actually convey the type of alarm, but require operators to visually read the alert on a display. Different sounds such as horns, whistles, sirens, bells, buzzers, and chimes have been used as audio warning signals. In addition, Kantowitz and Sorkin (1983) point out that other types of sounds such as elephant cries and women's screams have been suggested for use as alarms. However, false audio alarms or too many alarms can cause operator apathy. Under these conditions, operators have a tendency to be more concerned

with silencing the noise than attending to the alert. For example, auditory warnings in British civil aircraft are loud and startle the pilots. Communications are impeded since the alarm takes priority over the malfunction (British Technology Group, no date). For better communication between individuals, Patterson (1985) recommends that repeated tones for an alert be lowered after the first two bursts. Gilmore (1985) also is concerned about the length of auditory alarms interfering with communications and recommends alarms be presented only for a short duration.

Gaver (1988) recommends that auditory icons for alerts be dynamic and contain many high frequency sounds. This includes abrupt changes in amplitude and/or pitch. Patterson (1982) recommends an inter-pulse interval less than 150 ms for urgent alarms and over 300 ms for non-urgent alarms. Sorkin and Wood (1985) recommend a two or three priority level alarm that would indicate the confidence of the computer system.

Gales (1959) describes an experimental system for air traffic control that varied five different frequencies. A 2000 Hz tone indicated elevation was on "target." A 5000 Hz tone was used for a small deviation above target. An 8000 Hz tone was used for a large deviation above target. An 800 Hz tone was used for a small deviation below target and 100 Hz for a large deviation below target. The tones were steady and had equal intensity in both ears. This system was also binaural. Any deviation to the right or left was heard in the respective ear. Small deviations were interrupted at 1 Hz; moderate deviations at 1.12 Hz; and large deviations at 2 Hz. This system required operators to correctly identify 35 combinations of frequency, binaural intensity difference, and interruption rate. The author concluded the identification of interruption rates could have improved by using a wider range of rates.

Gales (1959) also describes the Flybar system developed for use in cockpits. Turn is indicated over binaural headphones by a repetitive sweeping motion of the signal from the left to right ear, or vice versa, depending on the direction of the turn. Bank is indicated by raising the pitch of the signal. Airspeed is presented by the repetition rate of a "put-put" signal. Gales (1959) states that pilots used this system successfully in test sessions.

Perceived Urgency of Warnings

Edworthy, Loxley, and Dennis (1991) indicate there is a problem between perceived urgency of a warning and the importance of the warning. These authors investigated the parameters of fundamental frequency, harmonic regularity, and amplitude envelope in their first experiment. A 530 Hz frequency was considered more urgent than 150 Hz. A regular amplitude envelope was perceived more urgent than a slow onset or offset. A 10% irregular harmonic series was perceived as more urgent than a regular one. In Experiment 2, these authors investigated fundamental frequency, delayed harmonics, and harmonic irregularity. In this experiment, a frequency of 350 Hz was considered more urgent than 200 Hz. A random harmonic series was perceived more urgent than the 10% irregular or 50% irregular harmonic series. "No delay" on harmonics was perceived more urgent than the "delayed" harmonics. In Experiment 3, two levels of rhythm and three levels of speed were studied. All pulses were equally spaced in the regular rhythm and syncopated in the irregular rhythm. The fast level of speed was twice as fast as the moderate level which was twice as fast as the slow level. The regular rhythm with the fast speed was considered the most urgent. In Experiment 4, the fast speed with four repetitions was perceived as most urgent. Results confirmed that speed has an effect on perceived urgency. A large pitch range was judged to be more urgent than a small or a moderate pitch range. Pitch was a major factor for subjects to discriminate between warnings.

Hillier and Edworthy (1989) studied the parameters of number of repetitions plus speed and length upon perceived urgency of a sound. The results showed increases in individual parameters increased the perceived urgency. Edworthy and Patterson (1985) noted the shorter the time between pulses, the more urgent the burst and that a rising pitch contour can represent a more urgent alert. They recommended that urgent bursts remain at maximum level while less urgent bursts decrease at the end of the burst. In summary, the most urgent alert was created by raising the pitch and speeding up the entire burst. The pitch was lowered and the burst slowed for a non-urgent alert. When a high priority alert was presented, the urgent form of the burst was repeated. With lower priority, only background bursts were presented. The urgent form reappeared only if an operator did not respond to these alerts. These authors also indicated all of these alerts can be followed by a voice warning.

Auditory Retention

Patterson and Milroy (1980) studied how quickly listeners could learn to identify 10 auditory warnings in civil aircraft. Listeners learned the warnings in one 1-hour session. Retention was tested one week later. The subjects then relearned the warnings, and after performing a task lasting 45 minutes, the subjects' retention was tested again. Listeners learned four to six warnings quickly. Each additional warning required an extra five minutes of training. However, listeners did learn all of the warnings. The retraining stage showed that subjects returned to near perfect performance in a few trials. Duration of the warnings was 1.47 seconds. All warnings were equal in amplitude.

Sound Families

In an earlier section, the different types of icons were described. There are nomic icons; metaphorical icons, symbolic and abstract icons. Nomic icons sound like the event itself. Metaphorical icons make use of similarities between the event and the sound. Symbolic icons rely on social convention. Abstract icons are tones, whistles, horns, etc. (Gaver, 1986).

Blattner, et al. (1989), Gaver (1989), Patterson (1982), and Sumikawa (1985) all point out the importance of using families of sounds to represent similar events. Gaver (1989) suggests that families of sounds can be created by using the organization inherent in everyday events. In sound families, all auditory icons representing similar events would use variations of a basic sound. Gaver (1989) cites the example of the use of a metal sound for conveying information on a computer. He uses a metal sound for applications, a hollow metal sound for disks, and a different hollow metal sound for the trashcan. Gaver (1989) also extends this principle by using frequency and pitch to indicate size of the objects. For example, large objects make lower sounds than small ones or a large change is indicated by changing the octave in a dragging operation on the computer.

Gaver (1988) suggests the use of motives, short musical phrases, for system messages since motives are not usually annoying. Motives can be used when auditory icons are difficult to find. Blattner, et al. (1989) and Sumikawa (1985) describe how motives can be varied. A three-note motive is recommended since a tune can

become irritating if heard very often. These authors recommend that tones used as an auditory icon be selected from the same octave. Auditory icons composed of related and organized groups of sound elements are easier to remember than unrelated tones. Blattner, et al. (1989) states tonal sequences are easy for Western listeners to remember.

Voice Warnings

Voice output has been suggested to alert operators. Patterson and Milroy (1980) point out that a speech warning message must be qualitatively different from other voices in the working environment. Simpson, et al. (1987) and Sorkin, Kantowitz and Kantowitz (1988) suggest voice warnings consist of short phrases. However, an extra word to clarify meaning does not lengthen response time. As with other types of false alarms, false speech warnings can cause performance to degrade.

Sorkin, et al. (1988) evaluated two types of alarm systems. The first alarm system was a two-state system. In this system subjects were alerted by either a visual alarm or an auditory alarm signal. In the visual alarm, the color white indicated no signal and the color red indicated there was a signal. With the auditory alarms, no verbal message was presented when no signal was present. When a signal was present, the verbal message "check signal" was heard. The second alarm system was a four-state system. In the visual alert, the color white was used when no signal was present. The colors green, yellow, and magenta indicated varying levels of signal probability. With the auditory alerts, no verbal message was presented when a signal was absent as in the two-state system. The verbal messages, "possible signal," "likely signal," and "urgent signal" were heard for the signal probability. Subjects performed a continuous tracking task which simulated a pilot's control of an aircraft as the primary task. The level of tracking difficulty was divided into "easy" and "hard" tracking conditions. In seven of the sixteen experimental sessions, subjects simultaneously performed a diagnostic decision-making task which involved monitoring and detecting the signals on the visual display. The operator was aided with the task of monitoring the visual display in half of the experimental sessions by an automated monitor subsystem which triggered one of the four alarm displays (visual two-state, auditory two-state, visual four-state, auditory four-state). Measurements of tracking error were obtained on the primary tracking task while

measures of detection accuracy and reaction time were obtained on the second task. Results showed that the presence of the alarm systems improved tracking performance in the dual-task conditions but that the complex alarm displays yielded the same improvement as simple alarm displays (i.e., the four-state and two-state alarm conditions, respectively). These results indicate that the presence of an alarm system allowed the operator to adopt an attentional strategy that diverted resources to the primary (tracking) task; that is, requiring subjects to pay less attention to the secondary (monitoring) task.

Combined Auditory Icons and Voice Output

Gaver (1988) points out some information is more efficiently conveyed by auditory icons while other information is best conveyed by speech. He also points out the complementary nature of auditory icons and speech output can be exploited by developing hybrid systems that make use of auditory icons to reinforce voice output and nonverbal sounds. Stokes, Wickens, and Kite (1990) state that nonspeech signals may be more easily comprehended by users in a noisy environment. For military helicopters, a double burst of sound followed by a voice warning is recommended by Rood, Chillery, and Collister (1985). Each of the auditory warnings would have their own sound so the alert is recognized immediately. The voice warning would only support the auditory sound.

Sorkin, et al. (1988) also suggest the use of an alerting cue prior to the voice warning signal. There is some controversy concerning this combination. Research shows that an alerting cue helps when competing speech is present or when advisories are given in conjunction with voice warnings. Simpson, et al. (1987) found that pilots wanted speech reserved for only the most critical warnings. These authors also report that response is faster to voice warnings than tones. Hakkinen and Williges (1984) tested synthesized voice warning messages with an air traffic control task. The results showed a cue before the alert lengthened response time. In contrast, these authors found when synthesized speech was used for multiple functions, more messages were detected with the alerting cue than without it. Mulligan, et al. (1984) suggests that presenting a cue signal after an auditory message may enhance memory for the message contents.

Scope of the Study

With the many alerts presented to tactical operators, a combination of auditory icons and voice warnings would be useful in the Combat Information Center (CIC). It is first necessary to focus research on the effect of auditory icons on alert detection in the CIC. The current research studied how the four different types of icons affected accuracy on alert detection and a visual task, and response time for detecting the alerts. Alerts and icons were selected with the help of the subject matter expert and other naval personnel from Fleet Combat Training Center, Pacific and the USS *LAKE CHAMPLAIN*. Alerts were selected on the basis of how well the different icon types would map with the alerts. There were four alert types. Icon families were created and developed for each of the alert types. There were three specific alerts in each alert type for a total of 12 alerts. For the first alert type, nomic icons were used. The family consisted of three variations of a sound simulating anti-submarine warfare launches. For the second alert type, a metaphorical icon family was used. For the third alert type, a symbolic icon family was used. The fourth alert type used abstract icons. Three variations of tones were heard. Subjects answered displayed questions and entered data while waiting for an alert.

It was hypothesized that both voice and auditory icons would significantly improve accuracy in detecting and discriminating alerts when compared to the control condition (buzzer condition). It was also hypothesized that both voice and auditory icons would decrease response time compared to the control condition (buzzer condition).

METHOD

Subjects

The subjects were 18 active duty Navy enlisted personnel, all males, from Fleet Combat Training Center, Pacific and the USS *LAKE CHAMPLAIN*. Most of the subjects were operations specialists in the Navy. A few subjects were sonar technicians or fire control technicians.

Workstation

The workstation consisted of a Macintosh Computer with two monitors, a touch pad, a mouse, a keyboard, and headset. See figure 1. The 20-inch large screen monitor was the geographical tactical

display. In the upper 1-inch section of the display, questions appeared (i.e., How many hostile submarines are north of ownship?). Subjects used the numeric keypad on the keyboard to answer questions concerning "how many." For questions such as, "hook the hostile aircraft closest to ownship," subjects used the mouse to place the cursor on the symbol, and then pressed the mouse button.

The smaller monitor was the Character Read-Out display (CRO). The CRO display was situated above the tactical display so that the workstation simulated the shipboard consoles in the CIC. All visual alerts that accompanied the auditory alerts, were presented on the CRO display. The alerts were presented at the top of the display and the status information appeared below the alert. Subjects were required to monitor both displays.

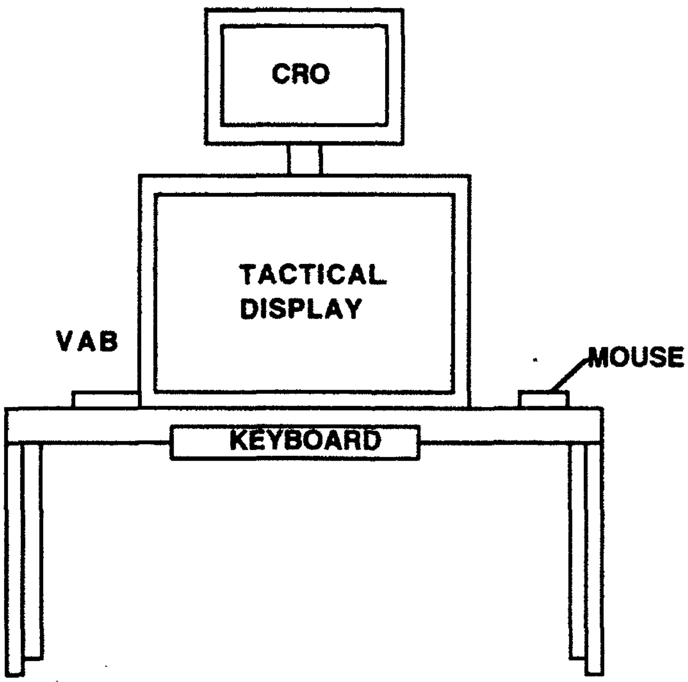

Figure 1. Workstation configuration

The auditory icon and voice alerts were heard on the headsets along with the background noise. On the touch pad (See figure 2) the "buttons" that represented the variable action buttons (VAB) were displayed. The subjects pressed the VAB "button" displayed on the touch pad to indicate which alert was presented. Subjects' responses and the correct answers were recorded by the computer for both the questions and the alerts along with the response time to alerts.

ASW Launches	**No Runout**	**Runout**	**Vertical Launch**
Illuminator Faults	**Illuminator Fault 1**	**Illuminator Fault 2**	**Illuminator Fault 3**
Harpoon Status	**Harpoon Upgrade**	**Harpoon Downgrade**	**Harp Attack Phase in Progress**
Radar Jams	**Jam 49**	**Jam 55**	**Jam 92**

Figure 2 - Simulated variable action buttons presented on the touch pad

<u>Experimental Design</u>

The experimental design was a 3X4X3 (Condition X Alert Type X Specific Alert) within-subject design. See figure 3. The three test conditions were: (1) alerts presented with voice advisories; (2) alerts presented with auditory icons; (3) alerts presented with buzzers to simulate present conditions. There were four different

BUZZER CONDITION												VOICE CONDITION												AUDITORY ICON CONDITION											
ASW Alerts			Illuminator Alerts			Harpoon Alerts			Jam Alerts			ASW Alerts			Illuminator Alerts			Harpoon Alerts			Jam Alerts			ASW Alerts Iconic			Illuminator Alerts Abstract			Harpoon Alerts Metaphor			Jam Alerts Symbolic		
No Runout	Runout	Vertical launch	Illum Fault 1	Illum Fault 2	Illum Fault 3	Harp Upgrade	Harp Downgrade	Harp Attack Phase in Progress	Jam 49	Jam 55	Jam 92	No Runout	Runout	Vertical launch	Illum Fault 1	Illum Fault 2	Illum Fault 3	Harp Upgrade	Harp Downgrade	Harp Attack Phase in Progress	Jam 49	Jam 55	Jam 92	No Runout	Runout	Vertical launch	Illum Fault 1	Illum Fault 2	Illum Fault 3	Harp Upgrade	Harp Downgrade	Harp Attack Phase in Progress	Jam 49	Jam 55	Jam 92

Figure 3. Experimental Design

types of alerts. The first alert type consisted of ASW Launch alerts. The second type consisted of illuminator faults. The third type were harpoon alerts and the fourth type were jams. There were three specific alerts for each alert type (i.e., illuminator fault 1, illuminator fault 2, illuminator fault 3) for a total of 12 alerts. See table 1. Based on the literature review, families of sounds were used for the four different types of alerts in the auditory icon condition. For the ASW alerts, nomic sounds were used. For the harpoon alerts metaphorical icons were used. For the illuminator and jam alerts, abstract and symbolic icons were used, respectively. Table 1 shows the sounds that were used for each alert in the auditory icon condition. For the voice advisory condition, the alerts were stated as shown in the "Specific Alert" column. Buzzers were used for alerts in the Buzzer condition. All auditory icons and buzzers were presented for a duration of 1.5 seconds. Visual alerts accompanied the auditory alerts in the experiment. There were a total of 60 alerts presented during each 20-minute scenario for each condition, approximately one every 20 seconds. Subjects heard a total of 180 alerts for all three conditions. Alert conditions were counterbalanced.

Except for the buzzer condition, alerts were presented through the headset. The buzzers emanated from the computer, so that actual conditions in the CIC were simulated. In addition, subjects heard the recordings of CIC communications in the headset. Subjects heard two channels, one in the right ear and one in the left ear. The alerts were presented to both ears. The subjects could select volume that was comfortable to them. The same volume was used for both alerts and the background recordings. The only difference was that the alerts were presented to both ears while subjects heard different channels in each ear.

The scenario consisted of a geographical tactical display with 50 to 70 symbols presented on the display. These symbols moved in a dynamic situation. Each scenario was 20 minutes long for each alert condition (icon, voice, buzzer) for a total of 60 minutes. The reason for displaying the questions on the tactical display was the necessity for separating the redundant visual alerts on the CRO from the visual task.

Table 1. Auditory icon alerts with sounds.

Alert Type	Specific Alert	Sound Used
ASW Launch (Iconic or nomic Icons)	No Runout	Water Circling in Bowl (Blip, Glug)
	Runout	Whoosh through Water
	Vertical Launch	Missile Sound, Splash in Water
Illuminator Downgrade (Abstract Icons)	Illum Fault 1	Dit (short tone)
	Illum Fault 2	Dit, Dit (2 short tones)
	Illum Fault 3	Dit, Dit, Dit (3 short tones)
Harpoon Status (Metaphorical Icons)	Harp Upgrade	Harp Up
	Harp Downgrade	Harp Down
	Harp Attack Phase in Prog	Harp high and low notes alter
Jam (Symbolic Icons)	Jam 49	Bagpipes 1
	Jam 55	Bagpipes 2
	Jam 92	Bagpipes 3

Procedure

Subjects read the instructions before training began. Subjects' training for each stage was as long as necessary for them to become fully competent in each task. Subjects were first trained on the symbols. All subjects were familiar with the Naval Tactical Data System (NTDS) symbols. Subjects then learned how to respond to the questions concerning the use of the keypad. Subjects then learned how to respond with the mouse to answer the "hook"

questions. When subjects were familiar with the visual task, the training on the alerts began. Subjects first listened to the sound for each alert in the condition presented first, until they could identify the sounds easily. The subjects then heard the alerts in a scenario and practiced the alerts alone by pressing the space on the touch pad that corresponded with the alert they heard. Subjects practiced until they were able to identify and respond to each alert with 100% accuracy. Subjects were fully trained on each alert condition prior to beginning testing in each condition. For example, if a subject received the auditory icon condition first, then the subject was trained in that condition first. Following training, the subject was tested on the auditory icon condition. If the voice advisory condition followed, the subject was then trained on that condition before testing began, and so on. In the final training stage the visual task and the alerts were integrated and the subjects practiced on a scenario. In all training stages, subjects received auditory feedback from the computer on whether their response was correct or incorrect. Testing then began on the first alert presentation condition. In summary, subjects were trained on the symbols and the visual task initially. However, subjects were trained on the alerts before each test condition.

Subjects sat at the workstation during testing and training. The background recordings from the CIC were heard through the headsets during the test. The sound level was the same for the alerts and the background recordings. Subjects were allowed to rest between the three test conditions. After all tests were finished, subjects were asked for input on the new alert presentation methods.

RESULTS

Error Analysis on Alerts

The Bio-Medical Data Processing (BMDP) statistical program was used for the analyses of variance. Newman-Keuls comparison tests were also performed on the data. First a 3X4 (condition X alert type) within-subject analysis of variance was performed on the error data. See table 1 in Appendix 1. The three conditions were voice, auditory icons, and buzzers. The four alert types within each of the three conditions were ASW launches, illuminator faults, harpoon status, and radar jams. The main factor of condition was significant [$F(2, 34)=5.14$, $p=0.01$]. Subjects made the least mean errors in the voice condition (3.5), followed by the auditory icon condition (5.3),

and the buzzer condition (6.0). Alert type was also significant [$F(3, 51)=10.25$, $p<0.01$]. Subjects had more mean errors in ASW (1.76) and harpoon alerts (1.93) than in the illuminator faults (0.61) and radar jams (0.69).

The condition X alert type interaction was also significant [$F(6, 102)=3.17$, $p=0.01$]. Table 2 shows the mean errors for each alert type in each condition. For ASW alerts where nomic icons were used, subjects performed better in the auditory icon condition. Voice was superior to the other conditions for the harpoons and jams. There were no significant differences between conditions for the illuminator faults.

Table 2. Mean errors for each specific alert type in each condition

CONDITION			
Alert Type	Voice	Auditory Icon	Buzzers
ASW Launches (Iconic or Nomic Icons)	1.83	1.06	2.39
Illuminator Faults (Abstract Icons)	0.44	0.50	0.89
Harpoon Status (Metaphorical Icons)	1.06	2.33	2.39
Radar Jams (Symbolic Icons)	0.17	1.33	0.56

The data were then analyzed with a 2X3 (performance level in control condition X condition) mixed factorial analysis of variance to determine what effect the alert presentation method had on subjects with high errors in the control condition. See table 2 in Appendix 1. Subjects were divided into two performance levels: subjects who had many errors in the control condition (buzzer condition) and subjects who had none or few errors in the control condition. Specific alert types were not analyzed in this data. Again this analysis showed condition to be significant. The between-subject factor, performance level, was also significant [$F(1, 16)=7.11$, $p=0.02$]. There were significant differences between those subjects with many errors and those with few errors. The high error group had a mean of 6.3 errors across all conditions and the low error group had a mean of 3.2 errors. There was an interaction between condition and performance level [$F(2, 32)=7.21$,

p<0.01]. Table 3 shows the mean errors in each condition for subjects with high errors and subjects with low errors. Significant differences between conditions were present with the high error group. Mean errors for subjects with many errors were: voice = 4.44, auditory icons = 5.33, and buzzers = 9.11. Both voice and auditory icons decreased errors for personnel who had many errors in the control condition. There were no statistically significant differences between conditions for highly accurate (low error) personnel.

Table 3. Mean errors in each condition for subjects with high errors and subjects with low errors in the control condition

CONDITION	HIGH ERROR GROUP	LOW ERROR GROUP
Voice	4.44	2.78
Auditory Icons	5.33	4.11
Buzzers	9.11	2.78

A 2X3X4 (performance level X condition X alert type) analysis of variance was performed to determine differences between the high error group and low error group on the alert types in each condition. See table 3 in Appendix 1. Condition, performance level, condition X performance level, alert type, and condition X alert type were all significant. Mean errors for each group in each alert type for each condition are presented in table 4 and figure 4. Fewer errors were made for ASW alerts in the auditory icon condition than the other

Table 4. Mean errors for high and low error groups in each alert type for all conditions.

ALERT TYPE	HIGH ERROR GROUP			LOW ERROR GROUP		
	Voice	Icons	Buzz	Voice	Icons	Buzz
ASW Launches (Iconic or Nomic Icons)	2.00	1.33	3.22	1.67	0.78	1.56
Illuminator Faults (Abstract Icons)	0.89	0.44	1.00	0.00	0.56	0.78
Harpoon Status (Metaphorical Icons)	1.56	2.78	4.00	0.56	1.89	0.78
Radar Jams (Symbolic Icons)	0.00	1.89	0.89	0.33	0.78	0.11

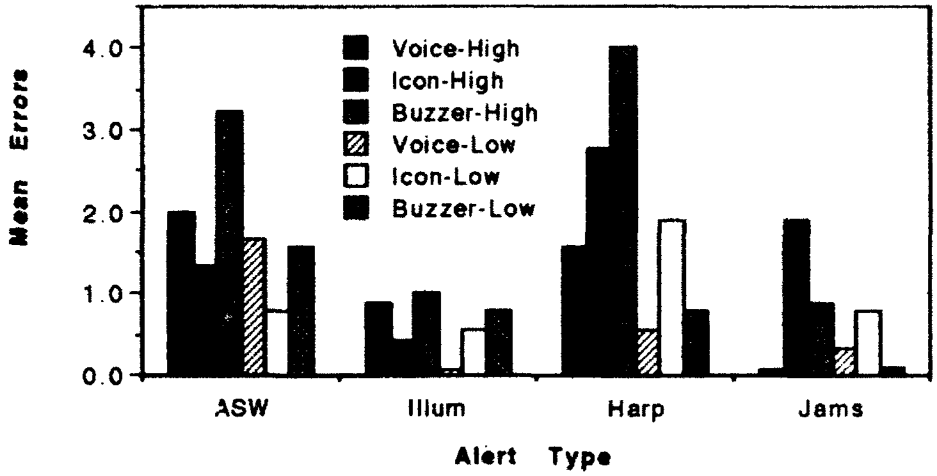

Figure 4. Mean errors for both high and low error groups.

two conditions for both the high and low error groups. There were no significant differences between conditions for illuminator faults. Voice was superior for the harpoon alerts. However, the metaphorical icons used in the auditory icon condition did decrease errors for the high error group when compared with the control (buzzer) condition. The voice condition improved performance on jam alerts for both groups of subjects. Both groups made many errors with radar jams in the auditory icon condition where the symbolic icon (bagpipes) was used

Response Time

A 3X4 (Condition X Alert Type) analysis of variance was performed on the response times. See table 4 in Appendix 1. The main factor of condition was significant [$F(2, 34)=8.92$, $p<0.01$]. Overall voice (3.4 seconds) had the lowest mean response time compared to auditory icons (4.0) and buzzers (3.8). Alert type was also significant [$F(3, 51)=7.56$, $p<0.01$]. Response time was highest for the harpoon alerts (4.0), followed by the illuminator faults (3.75), the ASW alerts (3.67), and the radar jams (3.55). A 2X3X4 (Performance Level X Condition X Alert Type) analysis of variance was performed to determine differences between the high and low error groups. There were no differences in response time.

Accuracy on the Visual Task

Subjects responded to questions asked on the display by hooking a particular symbol or by entering data on the keypad after searching the display for the number of requested symbols. The data from the visual task was first analyzed with a 3X2 [Condition X Question Type (hooks or questions)] analysis of variance. There were no significant differences between conditions or between hooks and questions. The data were then analyzed with a 2X3X2 (Performance Level X Condition X Question Type) analysis of variance to determine if subjects with many errors on alerts in the control condition also made more errors in the visual task than those subjects with none or few errors on the alerts. However, there were no statistical significant differences between groups. The visual task was not affected by subjects' performance on the alerts or the method of alert presentation. The mean errors for the visual task in each alert presentation condition were: voice = 6.9, auditory icons = 7.8, and buzzers = 8.7.

Correlations

Pearson Product Moment correlations were performed on the data using the Exstatix statistical program on the Macintosh computer. The correlation between alert accuracy and alert response time was significant (r=0.227) for all data. Error rates on the alerts in the voice condition and auditory icon condition were correlated with error rates on the alerts in the control condition (buzzers). This correlation was performed to verify that subjects with a high error rate on the alerts with buzzers also had a higher error rate in the voice and auditory icon conditions than subjects with lower error rates. The error rate for both voice output (r=0.626) and auditory icons (r=0.586) correlated significantly with the error rate in the buzzer condition. This means the subjects' relative ranking with respect to performance accuracy on the alerts remained the same. This test result confirmed that the analysis of variance accurately showed both voice and auditory icons helped those subjects who had many errors in the control condition.

Errors on the visual task were correlated with errors on alerts. The correlation between alert errors and visual errors was significant (r=0.411). Subjects who made more errors on alerts tended to make more errors on the visual task.

DISCUSSION

It was hypothesized that both voice and auditory icons would improve detection and discrimination of alerts compared to the buzzer condition. Overall, the hypothesis was proven to be true. When all the data were analyzed, the overall results showed that voice greatly improved detection and discrimination. Overall, auditory icons appeared to slightly help detection and discrimination. However, the analysis showed there were differences between conditions for each alert type. Auditory icons were superior to both other conditions for the ASW launches where the nomic icons were used. Voice alerts were superior for the harpoon status and jams although the metaphorical icons used for the harpoon status helped those subjects with many errors. Differences between the metaphorical icons used for the harpoon status may not have been clearly defined. The harp up that represented harpoon upgrade was in the same octave as the harp down that represented harpoon downgrade. The only difference was the upward movement of the harp tones for harpoon upgrade and downward movement of the tones for the harpoon downgrade. This may have caused some confusion.

For jams where symbolic icons were used in the auditory icon condition, the subjects did not perform well in the auditory icon condition. Thorning and Ablett (1985) and Gaver (1988) pointed out that similar repetition rates in a signal with alternating tones can cause confusion. Pitch varied for the alternating bagpipe tones used for the radar jams. However, the repetition rate was the same for the three specific radar jams. It is likely subjects confused the radar jams because the repetition rates were the same. In addition, all operators were not familiar with the sound that is normally heard during a radar jam. This symbolic icon was selected with the assistance of the subject matter expert who pointed out this sound is normally heard by electronic warfare operators. Some of the younger subjects (less senior in rank) may never have occupied a position where they were exposed to this symbolic sound. Thus, for them, the radar jam sound would have been an abstract icon rather than a symbolic one. There were no differences between conditions for illuminator faults. However, errors were minimal for illuminator faults in all conditions.

The subjects' data were divided into two groups: those with low errors and those with high errors in the control condition (buzzers). Both voice and auditory icons significantly decreased errors for those subjects with high errors in the buzzer condition. In other words, the high error group greatly improved so the high and low error groups were more equivalent. Both high and low error groups scored fewer errors with nomic icons used for the ASW launches in the auditory icon condition compared to the other two conditions. Apparently, the nomic icons greatly enhanced detection and discrimination for both groups. The abstract and metaphorical auditory icons helped the high error group. The low error group still had lower errors than the high error group. However, the most important thing is that the high error group showed a big improvement and reduced the spread between the high error and low error groups so that the group as a whole was more uniform in error rates.

It was also hypothesized that both voice and auditory icons would decrease response time. This was only half true. Voice output did decrease response time but auditory icons did not decrease the time. This finding is consistent with Simpson, et al.. (1987) who reported response to voice output is faster than with tones. It was noted that no statistical differences existed between response times for illuminator faults. This may be due to the serial nature of speech combined with the length of the phrase. Overall time differences are not as important as accuracy on detecting and discriminating alerts.

All of the subjects except one preferred the auditory icons and voice alerts. The subjects thought a combination of the two would provide a better system than the present buzzer system. Subjects were divided on which type of alert presentation would be best for the most urgent alerts. Some thought voice alerts would be best while others thought the voice would be ignored in a combat situation. Simpson, et al.. (1987) found that pilots preferred speech for critical warnings. However, pilots are finding the use of voice alerts to be irritating after long use. For this reason, auditory icons are better suited to alerts than the use of voice for all alerts. Some of the subjects thought auditory icons should be reserved for the most urgent alerts while other subjects favored icons followed by voice. Everyone stated the most urgent alerts would have to be designed for each console in the CIC separately. The current research and literature review has shown that auditory icons are

feasible for alerts in the CIC. With a good selection of icons, auditory icons should greatly improve performance in the CIC.

CONCLUSIONS

1. Overall, the results showed that both voice and auditory icons improved detection and discrimination of alerts compared to the buzzer condition currently used in the CIC.

2. Nomic icons helped subjects discriminate and detect alerts significantly better than voice alerts or buzzers.

3. Both voice and metaphorical icons decreased errors compared to the buzzer condition for those subjects with many errors.

4. Voice was superior to the symbolic icons and buzzers in reducing errors. The reason may be because the repetition rates of the symbolic icons were identical, thus, they appeared to confuse the subjects.

5. Although performance was good for all presentation methods where abstract icons were used for the auditory icon condition, both abstract icons and voice alerts slightly decreased errors.

6. Both auditory icons and voice alerts greatly improved discrimination and detection for those subjects with high errors. In other words, the lower performers showed a significant improvement and reduced the spread between high and low error groups.

7. Only voice alerts reduced response time. However, in navy tasks, small time differences are not as important as accuracy in detecting and discriminating alerts.

8. Auditory icons are better suited to frequent alerts than voice because voice becomes invasive and there is a possibility that voice may be "tuned out" in a combat situation.

9. Auditory icons for urgent alerts in the CIC need to be continuous. However, less urgent alerts should be lowered and repetition rates decreased after the initial sounds. For information alerts, only soft background sounds should be used.

10. Movie sound effects may be better than everyday sound effects for auditory icons. More research is needed for selecting the best sounds to use for alerts in the CIC.

11. Families of sounds need to be developed for related alerts.

12. Future research should focus on developing auditory sounds for all alerts in the CIC.

13. Auditory icon applications to 3-D sounds for alerts in the CIC need to be researched .

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APPENDIX A

ANALYSES OF VARIANCE

Table 1. Condition X alert type within-subject analysis of variance for errors.

Source	df	SS	MS	F	p
Condition	2	17.07	8.53	5.14	0.0112
Error	34	56.44	1.66		
Alert Type	3	77.94	25.98	10.25	0.0000
Error	51	129.31	2.54		
Condition X Alerttype	6	34.38	5.73	3.17	0.0068
Error	102	184.12	1.81		

Note: Numbers have been rounded to the second decimal place for everything but probability.

Table 2. Performance level X condition mixed factorial analysis of variance for errors.

Source	df	SS	MS	F	p
Performance Level	1	127.57	127.57	7.11	0.0169
Error	16	286.96	17.94		
Condition	2	49.04	24.52	4.90	0.0139
Condition X Per Level	2	72.15	36.08	7.21	0.0026
Error	32	160.15	5.01		

Note: Numbers have been rounded to the second decimal place for everything but probability.

Table 3. Performance level X condition X alert type mixed factorial analysis of variance for errors.

Source	df	SS	MS	F	p
Performance Level	1	39.19	39.19	10.15	0.0058
Error	16	61.80	3.86		
Condition	2	16.45	8.23	5.73	0.0075
Condition X Per Level	2	10.57	5.28	3.68	0.0366
Error	32	45.98	1.44		
Alert Type	3	79.07	26.36	11.05	0.0000
Alert Type X Per Lev	3	14.93	4.98	2.09	0.1200
Error	48	114.50	2.39		
Condition X Alert Typ	6	35.29	5.88	3.39	0.0045
ConXAlerttypeXPerLe	6	17.10	2.85	1.64	0.1438
Error	96	166.61	1.74		

Note: Numbers have been rounded to the second decimal place for everything but probability.

Table 4. Analysis of variance for response time.

Source	df	SS	MS	F	p
Condition	2	12.81	6.40	8.92	0.0008
Error	34	24.40	0.72		
Alert Type	3	5.81	1.94	7.56	0.0003
Error	51	13.07	0.26		
Condition X Alerttype	6	1.59	0.27	0.99	0.4362
Error	102	27.32	0.27		

Note: Numbers have been rounded to the second decimal place for everything but probability.

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The objective of this research was to develop and evaluate an advanced alerting technique that uses the auditory sense as well as the visual sense for alerts in the Combat Information Center (CIC). For a tactical officer to make critical decisions, time-critical information needs to be highlighted. Auditory icons were developed and an experiment was designed to test the effectiveness of auditory icons for alerting operational personnel. Auditory icons were compared to buzzers and voice alerts.

Overall, the results showed that both voice and auditory icons improved detection and discrimination of alerts compared to the buzzer condition currently used in the CIC. The data were analyzed according to subjects with high errors and subjects with low errors. Both voice and auditory icons significantly improved both alert discrimination and detection for those subjects with high errors. In other words, the high error group greatly improved so that both high and low error groups were more uniform. Only voice alerts reduced response time.

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